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Mechatronics for the Masses: a Hands-on Project for a Large, Introductory Design Class*

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The Department of Mechanical Engineering at the University of Minnesota has a new 'Introduction to Engineering' course with a hands-on approach to learning beginning engineering skills. Students undertake a series of design and dissection projects as a means for learning. The major project is a six-week assignment to 'design and build an autonomous machine that does something interesting for 45 seconds'. The machines are computer-controlled and require a combination of mechanics, electronics and software, the triad that comprises mechatronics. Resources, including extensive web-based tutorial information and take-home tool kits, were developed to allow students to design and fabricate their robots at home. Just-in-time lectures provide sufficient electronics and programming information to enable students to build robots to an appropriate level of sophistication. Each of the 200 students builds their own robot. During the six years the course has been offered, we have learned many lessons that make this mechatronics design project possible and a successful learning experience for students.

INTRODUCTION

'INTRODUCTION TO ENGINEERING' is the new, required, one-semester, lower division design course in the Department of Mechanical Engineering at the University of Minnesota. The course is built upon a foundation of dissection and hands-on design projects created to teach fundamental principles of mechanical engineering as well as specific engineering skills. It was taught as a pilot for 24 students in 1995–96 then became part of the required curriculum the following year when enrollment climbed to 105, and to 210 the year after that. It is now the largest course offered by the department.

One objective in developing the course was to demonstrate that hands-on projects could be realized in large courses. There is a widespread perception that core undergraduate courses with large numbers of students are incompatible with design-and-build projects because too much supervision and extensive shop and construction facilities are required and significant costs are incurred. In reality, creating and running a course based on hands-on projects can be only modestly more resource and staff intensive than a course with traditional problem sets. And what a student learns or doesn't learn is reflected just as much in a design, and the documentation associated with a design, as it is in a problem set. Thus, one of our objectives was to demonstrate that hands-on activities could indeed take place in large, undergraduate engineering courses.

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A computer-controlled robot design was chosen for the flagship design activity in the course because it is well within the scope of beginning engineering students and allows each student to realize a design which incorporates mechatronics. Smart products with embedded microcontrollers appear on the market daily and knowing the basics of mechatronics is essential for the modern engineering designer no matter what discipline he or she chooses to major in.

THE ROBOT PROJECT

Students have the last six weeks of the course to tackle this hands-on design project. Each student designs, constructs and tests their own autonomous, microprocessor-controlled 'robot'. The project charge is simple: 'Design and construct an autonomous machine that does something interesting for 45 seconds'. A few simple rules constrain this open-ended task. The machine must:

- have no interaction with the operator while running;
- fit on a 34×28 inch base;
- have at least one moving part;
- be microprocessor controlled;
- cost no more than $30 over the components provided;
- be safe.

We chose the BASIC Stamp from Parallax (www.parallaxinc.com) as the microcontroller for the robot project because it is simple to use, easy to program and inexpensive. Cost was a big driver in selecting the microcontroller because we loan one board to each of the 200 students. We use the older Rev. D version of the Stamp because it is affordable in large quantities ($27) and has sufficient complexity for this project. The Rev. D Stamp has eight digital I/O lines for interfacing to a maximum of eight simple sensors and actuators, for example LEDs, indicator lamps, sensing switches, motors, relays or solenoids. The hardware and programming language of the Stamp encourages yes/no sensing and on/off actuating methods. This may seem constraining, but actually is an advantage because it limits designs to those that are within the reach of the beginning student. The programming language is a simplified version of BASIC and surprisingly sophisticated machine behavior can be realized using only four or five statements from the instruction set. Software is developed on a host PC and downloaded to the Stamp through the PC parallel port. The program is retained in EEPROM when the power and programming cable are removed, and the microcontroller automatically boots up into the first instruction each time the 9 V battery is applied. We believe that the BASIC Stamp is the least expensive and easiest to use microcontroller on the market and is a perfect match for our project where we want students to experience all facets of design without having to wrestle with needlessly complex controllers.

The assignment culminates in a public, well-advertised Robot Show where approximately 200 working machines fill one of the University's largest meeting spaces, and students have a chance to show off their work to a jury of approximately 50 faculty and representatives from local industry. The show is well attended and has good media coverage including occasional spots on the television news. One advantage of having a show is that it provides an immovable deadline for the project. If you don't appear at the show with a robot, you fail the project. Students will confront these types of deadlines in their future professional career when they prepare a demonstration for an important trade show or finalize a prototype for presentation to venture capitalists. Events such as the Robot Show boost a student's confidence in their ability to create and provides a window into the excitement of engineering. Many students comment that the Robot Show solidified their commitment to engineering.

Projects are graded using a number of criteria. During the show, jury members evaluate robots for reliability, quality of construction, level of sophistication and innovation. After the show, staff members repeat the evaluation based upon project documents, which include a 'how-it-works' annotated drawing, a schematic and a commented code listing. The most important determinant of the project grade is whether the student has a working robot at the show which teaches the lesson that it is more important to have something simple that works reliably than something complex which only works on paper.

Over the six years we have been running the course, just about every idea imaginable has been realized by the student designers. At the Robot Show, one might see drink mixers, can crushers, a cracker spreader (complete with automated parts feeder), animated jungle dioramas, an automatic makeup applicator, a T-shirt folder, a single-string musical instrument that plays 'Hot Cross Buns' by varying string tension, a rope braider, a 12-step drink pourer, a mechanical tic-tac-toe machine, and a Barbie car that parks itself using infrared sensors for automated path following. Having a wide-open design task truly reveals the creative ability of today's students. Another advantage of an open-ended, non-competitive design task is that instructors are not burdened with developing a new competition each year.

PROJECT LOGISTICS

Formal instruction

Most students taking the course have little or no experience with practical electronics, no experience interfacing sensors and actuators to a computer and little concept of how to write computer code to perform real-time tasks. Lecture time is devoted to each of these topics, presented in a 'need-to-know' style tailored to the robot project.

Web resources

The project web site is an essential source of information for students. It contains examples of interfacing simple sensors and actuators to the microcontroller, written in a language and using graphics appropriate for novice engineers. Tools and techniques such as soldering are also described. Photographs of circuits and devices are useful because students learning electronics for the first time often have difficulty translating between schematics and actual hardware. The web content was largely determined by common questions asked by students.

Insuring steady progress

Several intermediate deadlines are included to insure that students make timely progress. For example, a concept drawing is due two weeks into the project and a tentative parts list one week later. A fully working subsystem must be presented in class at week four and extra credit is given if a working robot can be demonstrated one week prior to the Robot Show.

Individual project with group support

Although each student designs and constructs their own robot, working teams are formed so that designers can learn from their peers. During class, groups meet to discuss and assess concepts, to review ideas for sensors and actuators, and to trade information on which surplus stores have the best, low-cost parts for robots. Making the assignment unique provides each student with the experience of being responsible for all aspects of mechatronic design and project planning. Having groups provides students with peer support which reduces any feelings of anxiety or isolation.

Distributed shops

The project could not exist if the 200 students were required to construct their machines in the department student shop and program their microprocessors in the engineering school computer lab. Neither facility has the capacity nor supervision to handle such numbers. Our solution was to structure the project so that students could succeed using simple construction and code development methods, and then to provide each student with the appropriate tools so that they could develop their robot in their dorm rooms, in much the same manner that they would work on a problem set.

Each student is provided with a loaner kit that contains a digital voltmeter, an electric power drill, dial calipers for precision measurement, a wire-wrap tool for constructing electronic circuits, and a few basic hand tools. The loaner kit also contains components for use in the robot project, including the BASIC Stamp microcontroller board, one DC gear motor, one small DC motor, and a 12 V NiCd battery pack with recharger. The total value of each loaner kit is about $250. In addition each student receives a small set of electronic components, including several power transistors, some resistors, LED's, and wire. Because many students require additional electronic components over and above what is provided, and because purchase of components in small quantities is expensive and logistically complex for students without transportation, a small 'Robot Store' was created which sells a limited selection of components to students at cost. Students who do not have access to hand tools at home have the option of purchasing a complete kit of tools for approximately $60, in much the same way they might purchase a required textbook. An advantage of providing and encouraging the use of hand tools is that they are safer than many of the machine tools found in the shop, an important consideration when the majority of our beginning students are novices in tool operation.

Help

Design and debugging help is available during normal office hours. As the Show draws near, we open a large lab for students to complete their robots. The lab is not staffed at all hours, but students receive peer help from each other. The few days before the Show, we staff the lab almost continuously using course staff and expert student volunteers who took the course in previous years. At the show we have Robot Paramedics who roam the aisles looking for students in need, and in a side room have a fully-equipped and staffed Robot Hospital for robots in need of more serious fixes. Having these support mechanisms is essential to meet our goal of having 100% of the robots working at the Show.

LESSONS LEARNED

The robot project demonstrates that it is possible to implement a hands-on mechatronics design activity in a large course while minimizing costs and resources. We learned some lessons along the way:

- If the fabrication experience dominates the student's education, students can easily immerse themselves in building their design at the expense of gaining an understanding of what they are doing. It is important that a balance be established between completing the project and becoming familiar with the tools and process that underlie successful design practice. One way of doing this is to tie analysis and design together in meaningful ways so that students realize designs they have first analyzed. We are still working on ways to achieve this in the robot project.
- The most successful robots tend to be those where attention was paid to construction. Reliability is by far the biggest problem students encounter and by far the most prevalent reason for robots receiving a low score. It is essential that reliability be heavily rated in the scoring instrument and that students be continually reminded that a simple machine that works well will receive a better grade than a complex machine that barely works.
- Lower the barriers to students for building. If it is exceptionally difficult for a student to build, hands-on projects are doomed to failure. The distributed labs concept works well. By providing easy access to tools via the loaner kits, and easy access to common components via the store, students can and will spend more time on useful design activities rather than waiting in line for a drill press in the shop. By keeping the computer side simple, one can distribute a kit to each student at reasonable cost and can be reasonably sure that each student will have at least some kind of a mechatronics experience. Other options for introducing mechatronics in introductory courses are possible, including using more computation, sensing and actuating horsepower (Kurfess and Witzel, 2000). As the complexity of the hardware goes up, cost constraints force students to work in groups with one kit per group. Sophisticated hardware also means that more class time is needed to ensure students are able to gain the most benefit from the equipment. For our course, we took a complementary approach with a goal of providing students with relatively inexpensive systems that are easy to understand.
- Acquiring equipment for the loaner kits requires

a source of funding. We own approximately 225 kits valued at $250 each for a total capital cost of $56,000. The kits were funded from a variety of internal and external sources, but the money was relatively easy to obtain. The concept of providing equipment and components to undergraduate engineering students so they can participate in more hands-on activities resonates well with organizations which support academic initiatives.

- It is wise to purchase quality components for loaner kits. For example, during the pilot version of the course, the loaner kits included cheap ($18) digital voltmeters because of the desire to save money. Many of the meters had problems from the start, and many more were returned broken. Having learned our lesson, first-quality, industrial-strength voltmeters with a well-known brand name are now used.
- Maintenance and distribution of the equipment kits requires logistics and planning. With 200 students and multiple components per kit, keeping track can be challenging. A source of funds for equipment repair and replacement is needed. We hire an undergraduate student on an hourly basis to inventory and repair components as needed. Approximately 1 per cent of our inventory must be re-purchased each year to replace missing or broken equipment.
- Have a written contract which students sign when they receive their equipment kit. Our contract states that the student will receive an F for the course if the kit is not returned or if missing or broken parts are not paid for. The cost of each component is listed on the contract so that the value of the kit is clear from the start.
- The BASIC Stamp is a good match for beginning students who are able to learn its hardware and programming architecture with little difficulty. Ninety-five percent of our students have home PCs that are capable of running the Stamp development software. For those who wish to develop their code on campus, we purchased a small collection of outdated PCs for around $150 each that can run the Stamp application, and make them available for unsupervised 24/7 use by students. The PC's are sufficiently out of date that theft is not a problem, even when left in an unsecured location.
- Utilizing the Web as a design information database works. Design necessarily entails information gathering on the part of the designer. To make this easier for novice student designers, the instructor must gather information, both externally and internally generated, organize it in some reasonable fashion and place it on the Web. Although the time to create and maintain such a database is substantial, it ultimately will save time in student interactions. Also, today's students expect information to be on the Web and are extremely adept at finding and using it.
- Upper-level courses in our program do not have knowledge of mechatronics as a prerequisite, but seniors in the capstone design course have started to use the Stamp for projects where embedded computer control is required.
- It takes careful thought and planning to create meaningful hands-on activities. The rewards come from the bright, energetic students who become excited and motivated through their participation in challenging design projects.

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REFERENCES

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